

# STANDING WAVE LOCALIZED WITHIN ONE-DIMENSIONAL PHOTONIC CRYSTAL WITH DEFECT

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## Abstract

When a photonic crystal with defect is illuminated with a light pulse, a standing wave of light can be excited when the frequency of the defect mode is within the pulse spectrum and the temporal width of the light pulse is properly chosen. The results presented in this paper provide a new way to store light in photonic crystals.

**Keywords:** photonic crystal, defect mode, light pulse, light standing wave.

## 1. Introduction

Controlling light has always been the dream of many scientists. A lot of attention has been attracted to the possibility of capturing slow light and, in particular, to obtain a zero-velocity soliton in various schemes [1–5]. Using photonic crystals as an effective way to solve the problem became a field of intensive studies in the last twenty years [6–10]. Photonic crystals can be split into two classes according to their material constitution; one class consists of linear media while the other is nonlinear media. In photonic crystals consisting of nonlinear media, a fascinating phenomenon of the gap soliton can occur, which is promising for such applications as optical buffers and delay lines [5, 10]. In photonic crystals consisting of linear media, a defect mode can occur if a defect is inserted in the periodic structure of the photonic crystal.

If the photonic crystal is illuminated with monochromatic light with the defect-mode frequency, the light will be localized in the defect position [6]. The problem one should consider is whether the light would still be localized in the defect and how it maintains there. Namely this problem will be considered here. We look for a proper configuration of the photonic crystal (with linear media) and the light-source conditions under which the defect in the photonic crystal can capture some of the light-pulse energy. We show that the light standing wave can occur in the photonic crystal with the main energy stored within the defect. This is a tool for storing the light energy.

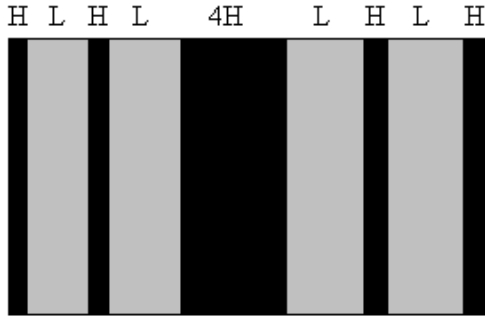


**Fig. 1.** Schematic diagram of the photonic crystal.

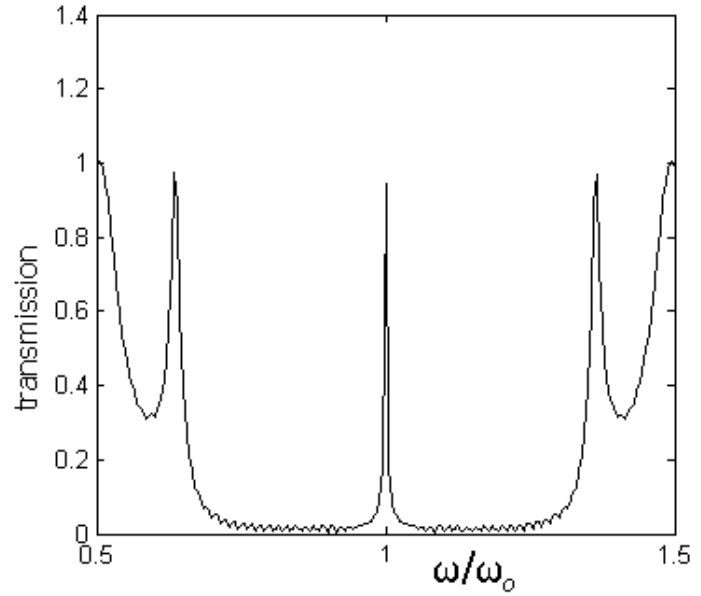


**Fig. 2.** The transmittance spectrum of the PC structure shown in Fig. 1.

## 2. The Model and Method of Computation

The structure under consideration is a one-dimensional photonic crystal (PC) with a finite length. Its schematic diagram is shown in Fig. 1 where H stands for layers with high dielectric index  $\varepsilon_h = 12.96$  and thickness  $d = 31.25$  nm, while L stands for layers with low dielectric index  $\varepsilon_l = 1.44$  and thickness  $3d$ . The two layers H and L stand for one lattice period equal to  $4d$ . The middle layer has the same dielectric index as the H layer and thickness  $4d$ . Thus, the whole structure can be written as  $(HL)_2(H)_4(LH)_2$  with the middle layer being a defect in the PC structure. In order to simulate the electromagnetic-wave propagation in the PC, we use the finite-difference time-domain (FDTD) method with perfectly matched layer boundary conditions. In a one-dimensional FDTD computation, the computation domain is first chosen with 31400 cells and each cell length is set as  $\Delta h = 0.625$  nm. Thus one period of the PC occupies 200 cells. The whole PC is set from cell number 15200 to 16200, while its defect is set from cell number 15600 to 15800. The other domain is free space. The time interval is chosen  $\Delta t = \Delta h/2c = 0.0010417$  fs ( $c$  is the light velocity) to satisfy the computation resolution. The computation space is split into total-field and scattered-field domains, in view of the total field – scattered field (TF–SF) formulation.

## 3. Results and Analysis

First we obtain the transmittance spectrum of the PC structure shown in Fig. 2, in which the defect mode occurs at the fundamental frequency

$$\omega_0 = \frac{2\pi c}{d\sqrt{\varepsilon_h} + 3d\sqrt{\varepsilon_l}} = 4188.8 \text{ THz.}$$

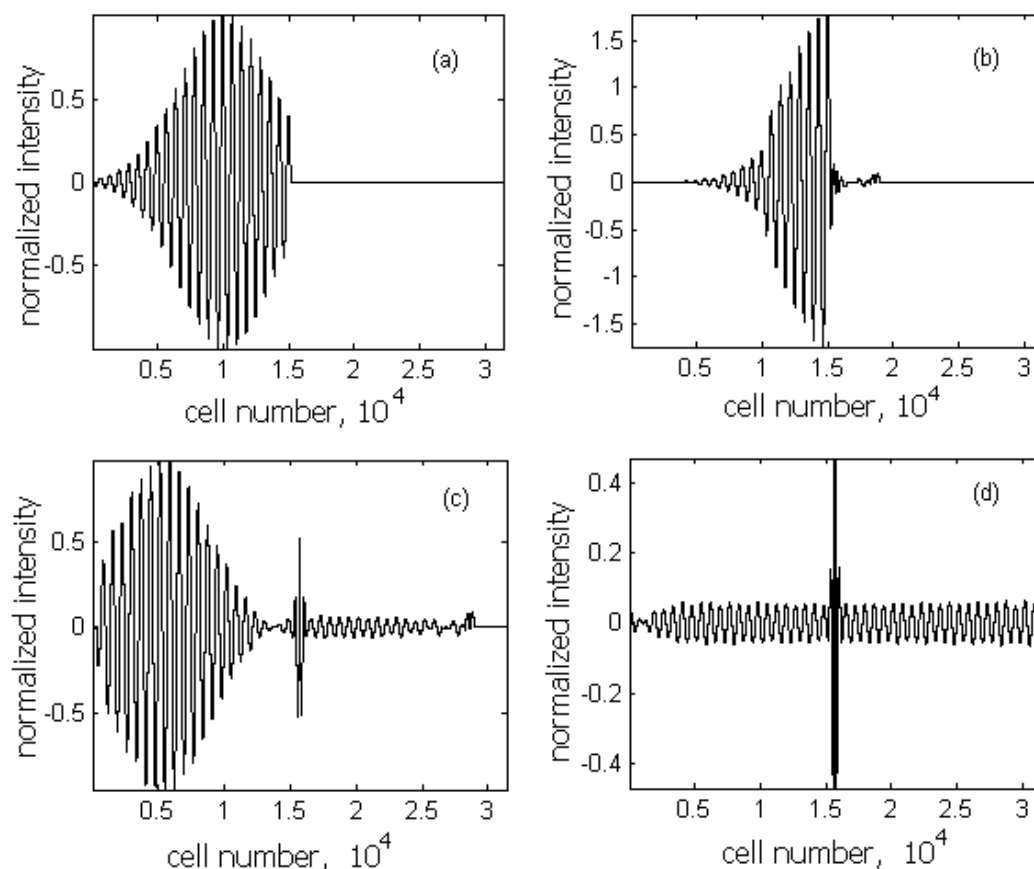


**Fig. 3.** The evolution of the light pulse at time  $t = 30$  fs (a), 40 fs (b), 70 fs (c), and 90 fs (d).

Because of the finite length of the PC, the spectrum of the defect mode has some width with the maximum at  $\omega_0$ . Then we excite a light pulse of the form

$$f(t) = \exp \left[ \frac{-(n - 10,000)^2}{10,000^2} \right] \sin [\omega_0(n - 10,000)\Delta t]$$

at cell No. 148, where  $n$  is the time-step number. The full pulse width is  $\sim 30$  fs and its center frequency is  $\omega_0$ . Figure 3 shows the light-pulse evolution at  $t = 30, 40, 70$ , and 90 fs. At  $t = 30$  fs, the pulse just reaches the PC. At  $t = 40$  fs, the pulse is interacting with the PC and the superposition of incident and reflective waves increases the wave peak value in comparison with the initial pulse. At the same time, the pulse energy starts to be absorbed by the PC defect. At  $t = 70$  fs, the pulse goes away from the PC due to the reflection, and a narrow light wave occurs in the defect center. At  $t = 90$  fs, though the main pulse has left the defect, the light of high intensity entering the defect is still localized inside the defect with small losses. By observing a series of snapshots of the evolution process of the light wave inside the PC afterward, we find that the wave inside the PC is just a standing light wave and its main energy is localized inside the defect. Figure 4 shows the temporal-spatial evolution of the electric field on all points on the whole defect. The origin of the space coordinate is taken at the front end of the defect.

The origin of the time coordinate is taken as the instant at which the light inside the defect has reached its steady state.

It is clearly seen that the standing light wave has a symmetrical structure with six nodes and five peaks. The biggest peak is just at the middle point of the defect. Comparing with the gap soliton in the PCs consisting of nonlinear media, this standing wave looks like a stationary soliton. One may ask how the standing light wave forms. As we know, a monochromatic light with the defect-mode frequency will be localized inside the defect position in the PC. Since the light pulse is a wave packet, it can be considered as a superposition of monochromatic-light waves with different frequencies. The center frequency of such a light pulse is just the same as that of the defect mode, but its spectrum is wider than that of the defect mode. When the light pulse reaches the PC, its elements with frequencies near  $\omega_0$  can enter the PC and will be mainly localized in the defect position; meanwhile, the other elements will be reflected back. For the frequency  $\omega_0$ , the optical thickness of one period of the PC is just  $\lambda/2$ . Then the wave with frequencies close to  $\omega_0$  inside the PC defect will be subjected to a strong Bragg reflection on both sides of the defect, i.e., once the wave enters the PC defect, it can hardly escape from it. On the other hand, the optical thickness of the PC is just  $3\lambda$ , so the wave inside the PC satisfies the condition of forming a standing wave. In Fig. 4, the light intensities at the two ends of the PC and the PC defect both reach zero and form wave nodes; the distances between two conjoint-nodes are just  $\lambda/2$ . The center of the defect is the position of the biggest wave peak.

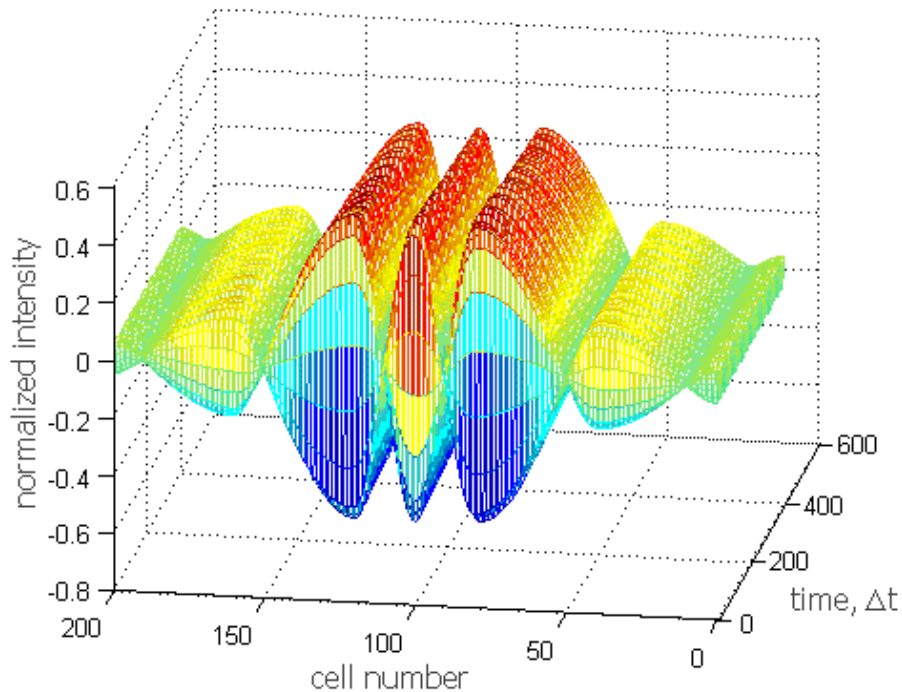


**Fig. 4.** The temporal-spatial evolution of the electric field at all points of the defect. The origin of the space coordinate is taken at the front end of the defect. The origin of the time coordinate is taken as the instant at which the light inside the defect has reached its steady state.

In considering the practical application of the above result, we should investigate how long the standing

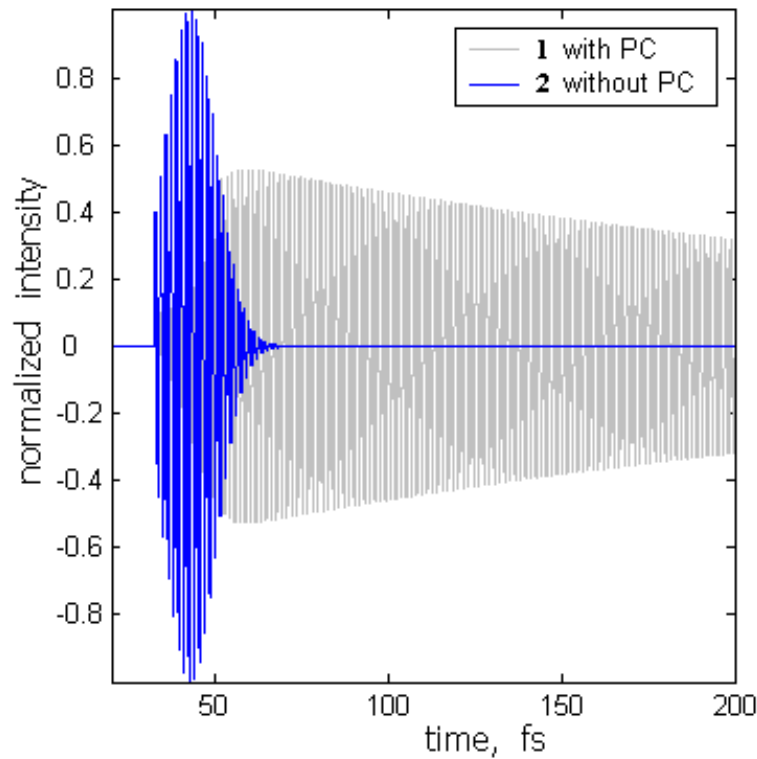


**Fig. 5.** Light intensity at the defect center of the PC structure  $(\text{HL})_2(\text{H})_4(\text{LH})_2$  at cell number 15700 versus time (curve 1). Curve 2 corresponds the the case where the PC structure was removed from the computation space.

wave is maintained. Thus we plot the change of the light intensity on the defect center at a cell number equal to 15700 with respect to time, as shown in Fig. 5 (curve 1). For comparison, we remove the PC structure from the computation space and also plot in the same figure the light intensity at the defect center (curve 2). In Fig. 5, the whole width of curve 2 is only  $\approx 36$  fs (from  $t = 32$  fs to  $t = 68$  fs), but the curve 1 only decreases from its maximum value (0.52) to the value 0.32 at  $t$  varying from 60 fs to 200 fs. Furthermore, we can also see that its maximum value decreases linearly with time with a rate of  $\Delta I / \Delta t = -1/700 \text{ fs}^{-1}$  ( $I$  is the light intensity) in the current-time domain.

In our computation, the time when the light intensity decreases from its maximum value to zero is 364 fs, which is almost ten times more than the whole width of the initial pulse. One can see that the time when curve 1 reaches its maximum is 28 fs more in comparison with curve 2; this is an indication that light travels in the PC more slowly than in free space.

Next, we consider the effect of the number of PC periods on the stationary soliton. We change the PC structure to  $(\text{HL})_4(\text{H})_4(\text{LH})_4$ . In spite of the fact that only four periods were added to the PC, light can hardly enter into the PC defect due to the increasing reflection, and the standing light wave was not formed in our computation. Then we increase the light-pulse width. We have chosen

$$f(t) = \exp \left[ \frac{-(n - 20,000)^2}{20,000^2} \right] \sin [\omega_0(n - 20,000)\Delta t]$$

as the light-pulse form and obtained the standing light wave. This is because with increase in the temporal

width of the light pulse, its spectrum width decreases, and the frequencies of more elements of the wave packet are closer to the defect-mode frequency.

## 4. Conclusions

In conclusion, we can state that at a suitable incident light pulse and appropriate PC structure, a stable and long-lived standing light wave can be obtained in PCs. In contrast to the other gap solitons in PCs, the standing light wave is created in the PC without any nonlinearity.

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